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SUSY Searches at CDF

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Disclaimer

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Abstract

A set of jet events with large amount of Missing E_T ($\not{E}_T$) from the Fermilab CDF experiment was analysed to search for SUSY signature. No significant signals were observed above the Standard Model background. Some effects of some SUSY parameters on the squark and gluino mass limits are presented.

1. SUSY Particle Productions and Decays at Tevatron Collider

In the Minimal Supersymmetric Standard Model (MSSM), the gauginos are complex mixtures of the higgsino, photino, zino and wino. Their masses are determined by five free parameters, which can be chosen as a SUSY Higgsino mass mixing parameter μ, the ratio of the two Higgs vacuum expectation values $\tan\beta$, and the masses of the charged Higgs, squark and gluino (m_{H^+}, $m_{\tilde{q}}$ and $m_{\tilde{g}}$). Most of the theoretical models also assume R-parity is conserved. This implies that SUSY particles are pair produced and that the lightest supersymmetric particle (LSP) cannot decay.

Gluinos and squarks are strongly interacting, thus they would be the SUSY particles with the largest production cross-sections at a $\bar{p}p$ collider. Fig. 1 show the expected $\tilde{q}\tilde{q}$, $\tilde{g}\tilde{g}$ and $\tilde{q}\tilde{g}$ cross sections for different squark and gluino masses. The branching ratios of gluino and squark decaying into various chargino and neutralino states depend on the the respective masses and mixing angles. In a scenario of a low mass gluino and a massless photino ($\tilde{\gamma}$) as the LSP, the decay modes become very simple. If $m_{\tilde{g}} < m_{\tilde{q}}$, the squark decays dominantly into $\tilde{g}q$ and the main gluino decay is $\tilde{g} \to q\bar{q}\tilde{\gamma}$. If $m_{\tilde{q}} < m_{\tilde{g}}$, then the gluino decays dominantly into $\tilde{q}\bar{q}$ and the main squark decay is $\tilde{q} \to q\tilde{\gamma}$. Since the photinos escape the detectors without any signature, the SUSY events would have two or more jets with a large amount of imbalanced transverse momenta.

The Fermilab Tevatron proton-antiproton collider operating at a center-of-mass energy of 1.8 TeV provides an unique opportunity for SUSY search. The typical luminosity during 1988-89 run was about $10^{30} cm^{-2} s^{-1}$.

The Collider Detector at Fermilab (CDF)[1] is a large detector for study of $\bar{p}p$ collisions at the Fermilab Tevatron. It has a fine-grained, projective-tower geometry covering most of the 4π solid angle with electromagnetic and hadron calorimeters. Its principal subsystems are the central scintillator sampling calorimeter ($|\eta| < 1.1$), the end-plug gas sampling calorimeter ($1.1 < |\eta| < 2.4$), and the forward gas sampling

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calorimeter ($2.4 < |\eta| < 4.2$), where the pseudorapidity $\eta = -\ln\tan\theta/2$, and θ is the polar angle. Inside the central calorimeter, a superconducting solenoid generates a 1.41 T magnetic field for tracking chambers surrounding the collision axis. The region $|\eta| < 0.63$ is instrumented with drift chambers for muon detection outside of the hadron calorimeter. Charged tracks with $|\eta| > 0.63$ associated with minimum ionization signals in the calorimeters are also considered muon candidates.

2. Analysis and Results from 1988-89 Data

2.1 The Missing E_T Trigger

The Level 2 and Level 3 $\not{E}_T$ triggers were installed in 1988-1989. The Level 2 $\not{E}_T$ trigger requires events to have

1. $\not{E}_T > 25$ GeV;

2. the leading calorimeter cluster has greater than 6 GeV energy deposited in EM calorimeters and no seed towers in the forward region.

Fig. 2 shows the Level 2 trigger efficiency based on a study from a jet data sample. For $\not{E}_T > 40$ GeV, it is over 90% efficient.

The Level 3 trigger algorithm removes the detector noises and corrects the 'Texas Tower'†. A dijet cut is used to reduced the QCD background. The dijet events are those having a jet ($E_T > 15$ GeV) within 30° opposite to the leading jet direction in ϕ. $\not{E}_T > 40$ GeV is required for those events.

2.2 SUSY Event Selections

The offline analysis eliminates known sources of detector noise, computes tower energies, reconstructs tracks, and applies the CDF jet algorithm which sums the calorimeter E_T within a cone of 0.7 in $\eta - \phi$ space [2]. Events with cosmic rays are rejected. The dijet events (as discussed in the previous section) are also removed from the data sample. Events are selected by requiring $\not{E}_T \geq 20$ GeV and ≥ 2 jets, where the jets are in the interval $|\eta| < 3.5$, have $E_T \geq 15$ GeV, and deposit between 10% and 90% of their energy in the EM calorimeters. This selection yields 1,226 events.

A series of more stringent cuts are made in order to get a final sample of events which could contain SUSY particles. The first of these cuts is designed to select events with a well measured large $\not{E}_T$ by requiring $\not{E}_T \geq 40$ GeV (281 events survive), and $\not{E}_T$ significance $S \geq 2.8$, where $S \equiv \not{E}_T / \sqrt{\Sigma E_T}$ [GeV$^{1/2}$] and the sum is over all calorimeter cells (257 events survive). The S cut removes most events with $\not{E}_T$ induced by measurement fluctuations. For an event sample with no muons, neutrinos or other non-interacting particles, we expect the S distribution to reflect the $\not{E}_T$ resolution of the detector. Fig. 3 shows the observed S distribution for dijet events (jet $E_T > 25$ GeV) to be adequately described by the CDF detector simulation program. This gives confidence that, for events with jets in this E_T range, the simulation correctly models the detector resolution.

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†Energy deposited in the calorimeter by low energy neutrons

We next required:

1. No muon candidates of transverse momentum $P_T > 15$ GeV/c. This rejects $W \to \mu\nu$ and $Z \to \mu^+\mu^-$ decays (230 events survive).

2. No calorimeter clusters with $E_T > 15$ GeV and $\geq 90\%$ energy deposited in EM calorimeters. This rejects $W \to e\nu$ decays (196 events survive).

3. No jet cluster within $\pm 30°$ in ϕ from the $\not{E}_T$ direction. This rejects mismeasured multijet events (124 events survive).

4. At least one central jet ($|\eta| < 1.0$) with a ratio of summed charged–track momenta to cluster energy ≥ 0.2. This rejects events where timing information from the central hadron calorimeter was unavailable to eliminate cosmic rays (116 events survive).

5. An interaction vertex within ± 60 cm of the detector center on the beam axis and no other beam interaction vertex (100 events survive).

Remaining events are inspected on a graphics display. We remove one beam-gas collision, one cosmic ray event, and five events with detector malfunctions. The final sample of 93 events has 71 events with two jets, 20 with three jets and 2 with four jets (jet $E_T > 15$ GeV).

2.3 The Standard Model Background

The main sources of non-SUSY background in the resulting $\not{E}_T$ plus jets data sample are from QCD multijet events in which the jet energy has been mismeasured, and events associated with W/Z production and leptonic decay. For W/Z plus jet events, if the lepton's P_T is below 15 GeV/c or it is out of the detector geometric coverage, it could become the SUSY background. Mismeasured QCD events could become background since the it resulted in the imbalanced E_T. Fig. 4 shows the angular separation between the third jet and the $\not{E}_T$ direction in ϕ before the cut 3 above applied. There are an overflow near $0°$ while the same distributions for SUSY signal and W/Z plus jet events are almost flat. This is a clear indication that one of the jet energy in these event is mismeasured which resulted in a large amount of $\not{E}_T$. This is also the motivation for the cut 3 above. The same distribution after cut 3 shows much less overflow near $0°$. It is estimated that 4 ± 4 QCD events still remained after the cut.

Backgrounds from W and Z production and decay which pass our selection cuts are calculated with a Monte Carlo program [4] and a simulation of our detector. This predicts 23 ± 8 $Z \to \nu\bar{\nu}$, 41 ± 15 $W \to \tau\nu$, 18 ± 6 $W \to \mu\nu$, and 9 ± 3 $W \to e\nu$ events in our data sample. The total predicted event rate from background (95 ± 19 events) and its associated $\not{E}_T$ spectrum agree well with the rate and spectrum for the 93 events in our data (Fig. 5).

We observe two events with $\not{E}_T > 150$ GeV. The highest $\not{E}_T$ event has $\not{E}_T = 185.9$ GeV with three jet clusters: $E_T = 183.9$, 33.8 and 11.3 GeV. The second highest $\not{E}_T$ event has $\not{E}_T = 167.8$ GeV with four jets: $E_T = 144.7$, 46.6, 19.3 and 16.5

GeV. The third of these jets contains an electron candidate with $P_T = 11.3$ GeV/c. The transverse mass calculated from the electron and $\not{E}_T$ vector is 57.2 GeV/c^2. The W/Z plus jets Monte Carlo calculation predicts 0.2 events with $\not{E}_T > 150$ GeV will pass our cuts. However note that this Monte Carlo program only simulates W/Z production with up to three jets. There could be background from top events, too. At this time, we do not consider it since the top quark is still to be discovered. We believe that the two observed events do not constitute a statistically significant deviation from the standard model prediction.

2.4 Squark and Gluino Mass Limits

To explore our sensitivity to a SUSY signal, we generate SUSY events using the ISAJET [5] Monte Carlo program (version 6.22) and EHLQ1, EHLQ2, DO1, and DO2 structure functions. The lowest rate comes from EHLQ1, which is used to provide a conservative production limit for SUSY particles. There are several sources of uncertainty in the predicted rate: ±6.8% in rate from the the integrated luminosity, ±10% in rate from the ±5% uncertainty in the energy scale, ±3% in rate from the uncertainty on the $\not{E}_T$ trigger efficiency, and ±15% from various sources in the Monte Carlo calculation — the choice of Q^2, α_s evolution and the limited number of events generated. The combined acceptance of the simulated detector and analysis programs for generated SUSY events is heavily dependent on the choice of squark and gluino masses. For the mass region we studied, it varies from 3% to 25%.

Our limits on $m_{\tilde{q}}$ and $m_{\tilde{g}}$ are based on a comparison of the observed $\not{E}_T$ distribution with predictions for the standard model background based on the Monte Carlo of Ref. [4] and the estimated QCD background discussed above, plus the SUSY contribution based on the ISAJET Monte Carlo samples. For each hypothesised $m_{\tilde{q}}$ and $m_{\tilde{g}}$ we fit the observed $\not{E}_T$ distribution over the full $\not{E}_T$ range using a binned likelihood method. The resulting upper limit on the rate of SUSY particle production is then compared with the predicted SUSY cross-section. Note that if the measured calorimeter energy scale is less than the true scale the predicted standard model contributions are reduced, and the limits are weakened. In extracting our limits to take into account this systematic uncertainty we have reduced the detector energy scale in the Monte Carlo simulation by 5%. The resulting region of the $m_{\tilde{q}}$ vs. $m_{\tilde{g}}$ plane excluded at 90% C.L. is shown in Fig. 6. The symmetric and asymptotic points on the limiting boundary are: $m_{\tilde{q}} = m_{\tilde{g}} = m = 225$ GeV/c^2, $m_{\tilde{q}} = 126$ GeV/c^2 (at $m_{\tilde{g}} = 5000$ GeV/c^2), and $m_{\tilde{g}} = 152$ GeV/c^2 (at $m_{\tilde{q}} = 5000$ GeV/c^2). We exclude at the 90% confidence level the existence of squarks and gluinos with masses less than 126 GeV/c^2 and 141 GeV/c^2 respectively.

Finally we extracted the limits shown in Fig. 7 for cascade decays with a particular choice of SUSY parameters: $\mu = -250$ GeV, $\tan\beta = 2$, and $m_H = 500$ GeV/c^2 as used in Ref. [6]. The weakened limits are due to cascade decays and non-zero LSP mass. For a gluino mass greater than 410 GeV/c^2, we can place no limit on the squark mass. It is worth to note that with this parameter set we chose, the degraded gluino mass limit $m_{\tilde{g}} > 90$ GeV/c^2 (when $m_{\tilde{q}}$ is large) is the result of

the cascade decay where the branching ratio for $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$ is only 34%; but when $m_{\tilde{g}}$ is large the branching ratio for $\tilde{q} \to q\tilde{\chi}_1^0$ is still about 100%, the reduced squark mass limit is the result of the large LSP mass ($m_{\tilde{\chi}_1^0} = 53$ GeV/c^2 when $m_{\tilde{g}} = 400$ GeV/c^2 and $m_{\tilde{q}} = 100$ GeV/c^2).

3. Status of SUSY Searches from 1992-93 Data

As the squark and gluino mass limits increases, the simple model with $m_{\tilde{\gamma}} = 0$ and no cascade is no longer valid. In MSSM there are five free parameters, we need a comprehensive method to study and present the limits on sparticle masses or other parameters. Such a study is on going. There is also the need to understand the background from WW, WZ and ZZ processes, as they will become important for high mass gluino and squarks.

The CDF has upgraded its detectors for the new run starting from 1992. The major improvements include the silicon-vertex detector which could provide information to tag b jet, the central muon upgrade and extension system which could improve muon identification and muon coverage.

The accelerator delivered more then $20pb^{-1}$ data from August 1992 to March 1993. CDF collected about $15pb^{-1}$ to tape.

3.1 Search for Squarks and Gluinos

A data set of integrated luminosity of $12pb^{-1}$ has been analysed. With the cuts similar to the previous section, 20 events were found to have $\not{E}_T > 90$ GeV with two or more jets. Their $\not{E}_T$ distribution is shown in Fig. 8. This is consistent with our previous observation that no significant excess events were found which suggested SUSY existence. More studies are underway to understand backgrounds and efficiencies.

3.2 Search for Charginos and Neutralinos

The increased luminosity provides us more opportunities in searching for SUSY particles. $\tilde{\chi}_1^+\tilde{\chi}_2^0$ could also be produced in $\bar{p}p$ collisions, although its cross section is small (< 10 pb). The decay mode $\tilde{\chi}_1^+ \to l\nu\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \to l^+l^-\tilde{\chi}_1^0$ results in trilepton event. This signal is very clean. We expect to be able to search for Charginos and Neutralinos in the mass region above LEP limits in this channel.

4. Acknowledgement

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SUSY Production at 1.8 TeV
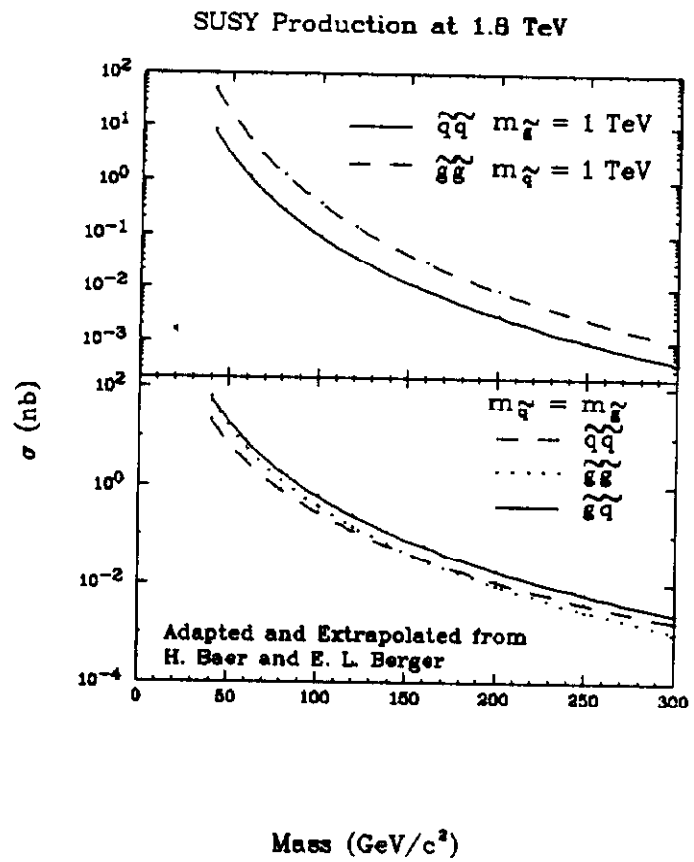
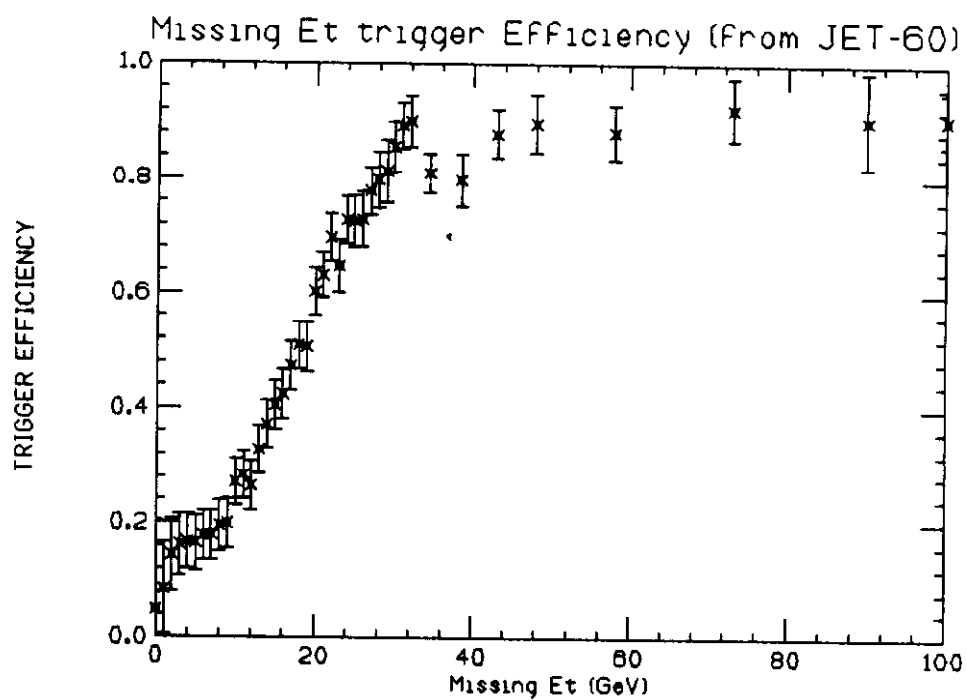Figure 1: The squark and gluino production cross section at Tevatron.

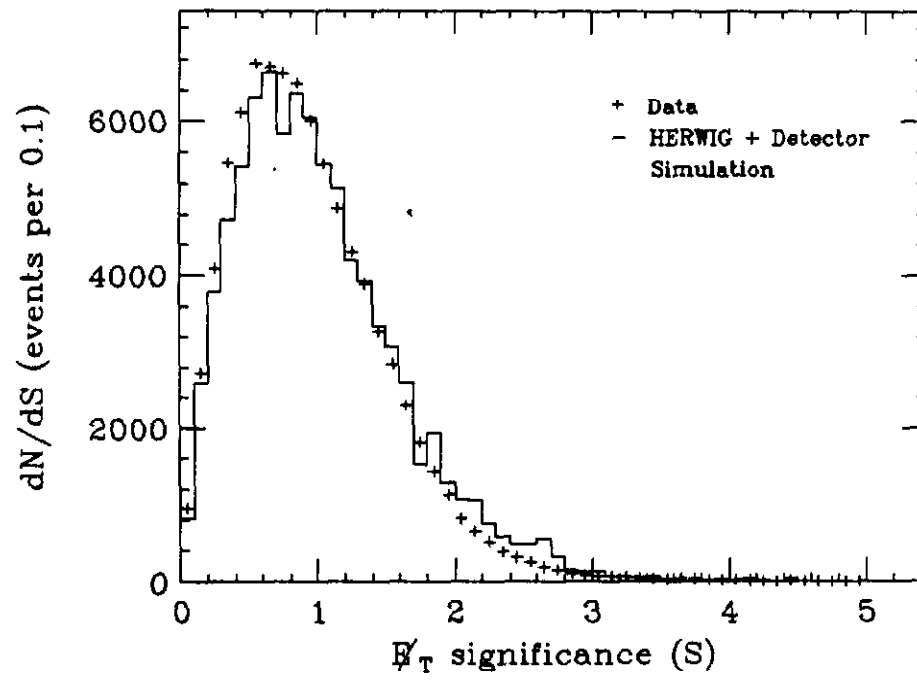Figure 2: The Level 2 $\not{E}_T$ trigger efficiency obtained from a jet date sample.

Figure 3: Missing E_T significance distribution for a jet sample (jet $E_T > 25$ GeV) compared with the predictions from the HERWIG [3] Monte Carlo and CDF detector simulation.

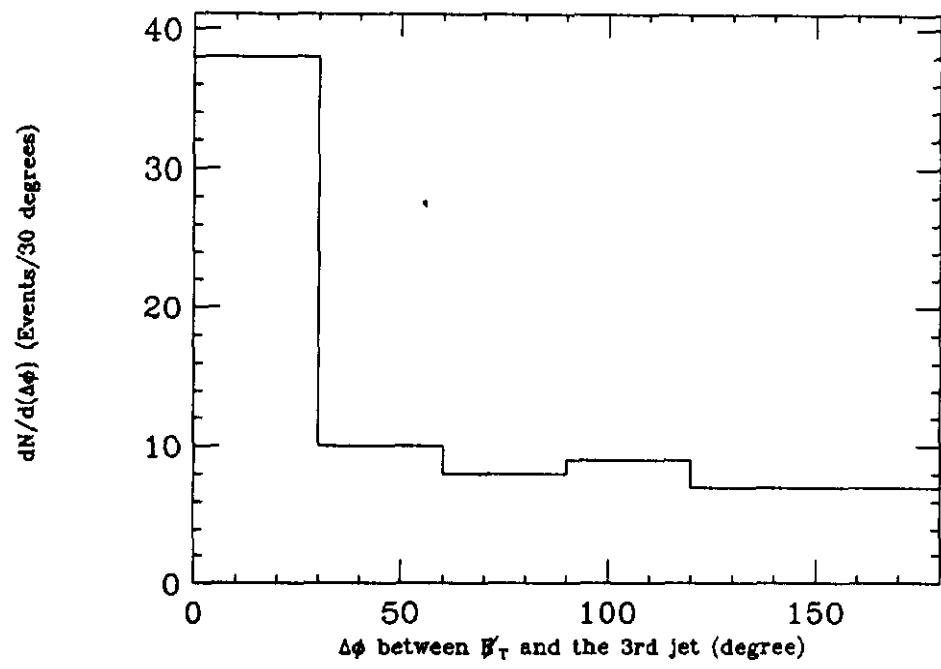Figure 4: The ϕ angular seperation between E_T and the third highest E_T jet.
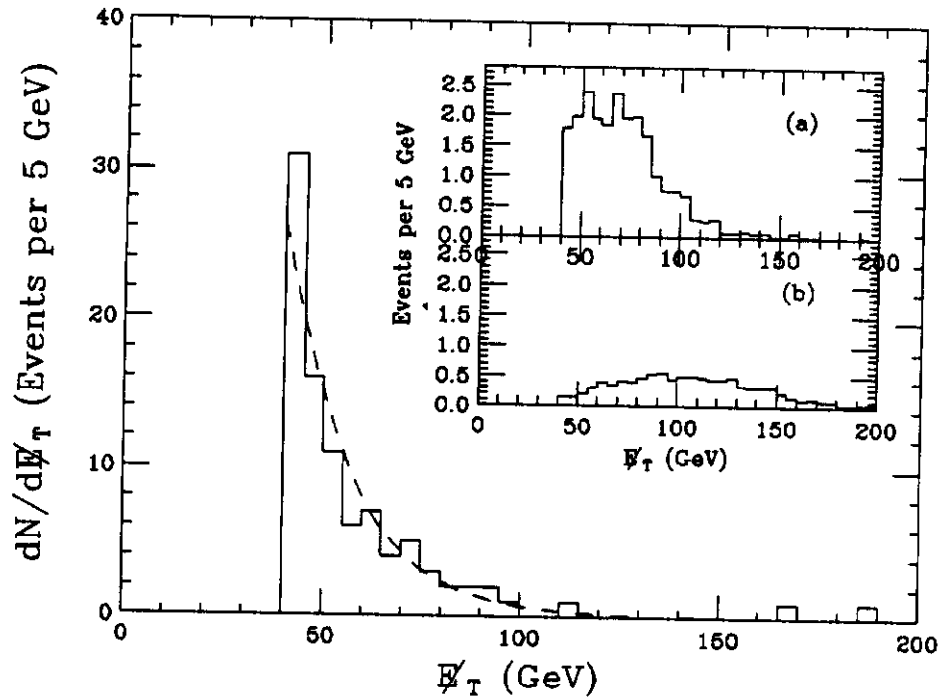
Figure 5: Missing E_T distribution (solid line) for the data set described in the text, compared with the estimated background predictions (dashed line) obtained using the Monte Carlo program of reference [4] together with the CDF detector simulation plus the estimated QCD background. Insets show predicted $\not{E}_T$ distributions for squark and gluino production from ISAJET (version 6.22) and the CDF detector simulation for (a) $m_{\tilde{q}} = 125\,\mathrm{GeV/c^2}$ and $m_{\tilde{g}} = 5000\,\mathrm{GeV/c^2}$, and (b) $m_{\tilde{g}} = 225\,\mathrm{GeV/c^2}$ and $m_{\tilde{q}} = 225\,\mathrm{GeV/c^2}$.
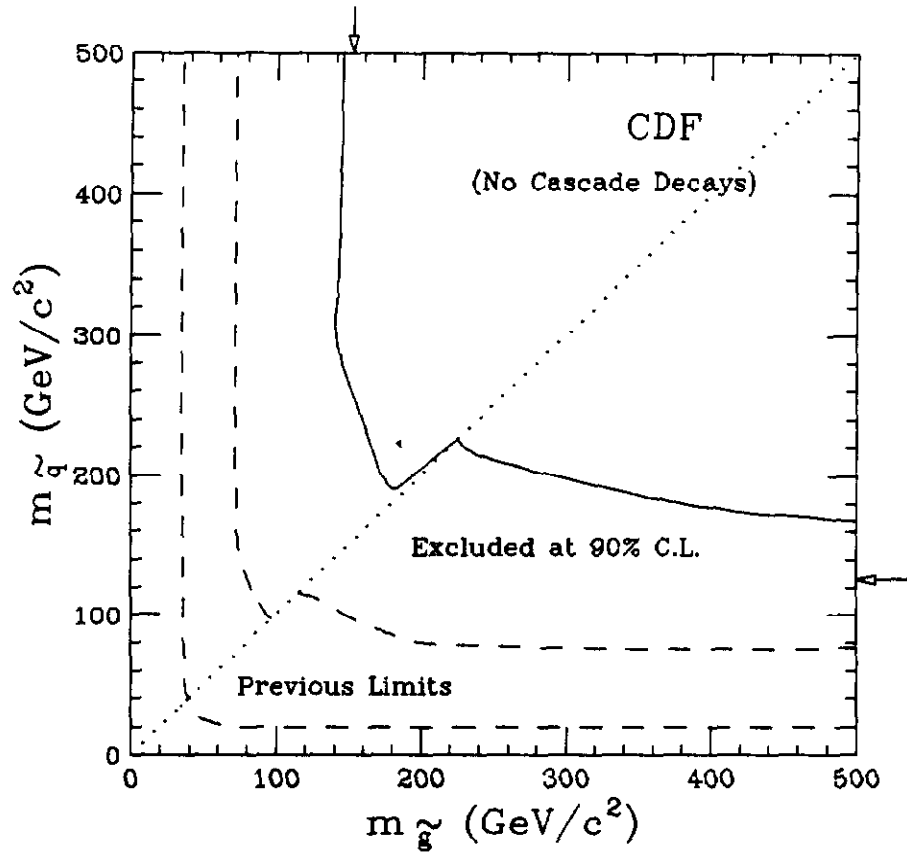
Figure 6: Squark and gluino mass limits for a version of SUSY with a light photino ($m_{\tilde{\gamma}} < 15$ GeV/c^2), six mass-degenerate squarks and no cascade decays. The region of $m_{\tilde{q}}$ versus $m_{\tilde{g}}$ plane excluded at 90% C.L. is shown. The dashed lines are boundaries of the region excluded by our previous analysis [7]. The solid line indicates the added region excluded by the present analysis. Asymptotic limits are indicated by the arrows. The discontinuity at $m_{\tilde{q}} = m_{\tilde{g}}$ reflects the change in the expected decay chain. Squark masses below 45 GeV/c^2 are excluded by data from LEP [8].
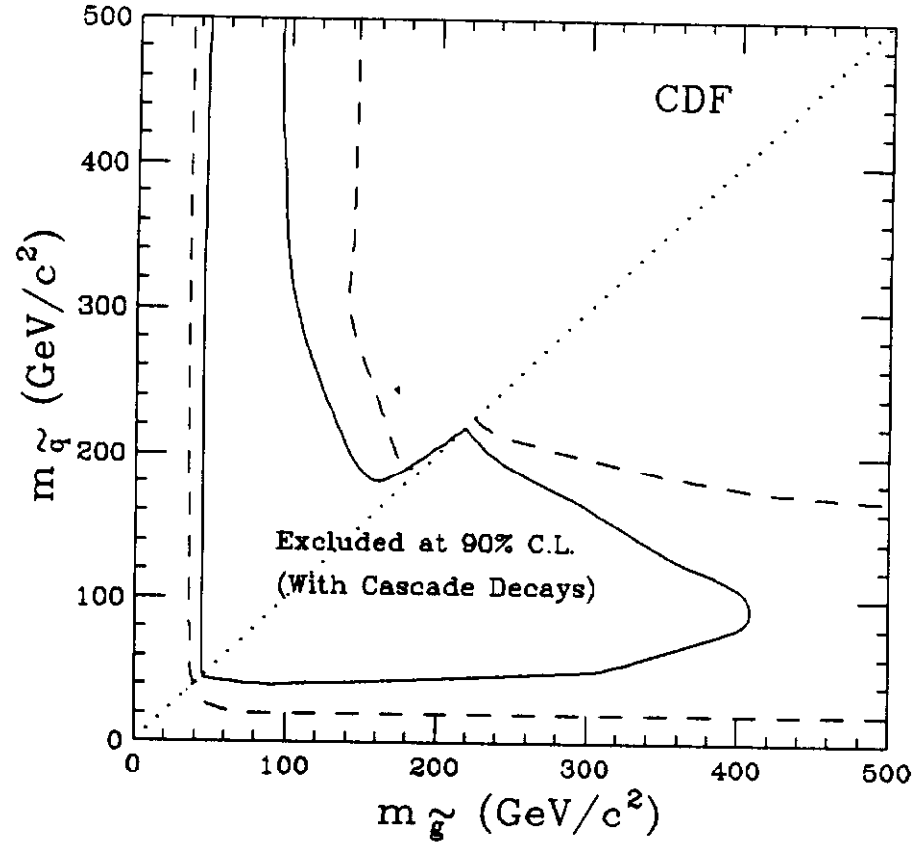
Figure 7: The shaded region of squark and gluino masses is excluded at 90% C.L for a version of SUSY with cascade decays, $\mu = -250$ GeV, $\tan\beta = 2$, and $m_H = 500$ GeV/c^2. For comparison, the dashed line shows the limits corresponding to no cascade decays.
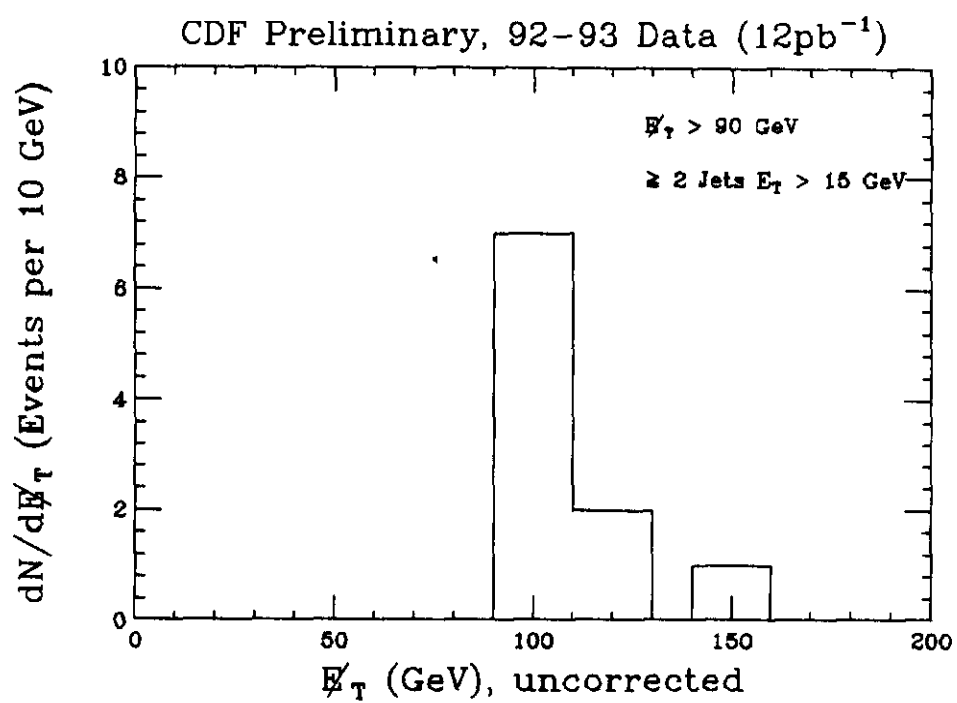
CDF Preliminary, 92–93 Data (12pb^{-1})

$\not{E}_T > 90$ GeV

≥ 2 Jets $E_T > 15$ GeV

$\not{E}_T$ (GeV), uncorrected

dN/d$\not{E}_T$ (Events per 10 GeV)

Figure 8: Missing E_T distribution for a 1992-93 data set coresponding to an integrated luminosity of $12pb^{-1}$.